DRAFT FINAL INTERIM FEASIBILITY STUDY REPORT

APPENDIX A: CHEMICAL FATE AND TRANSPORT MODELING

SAN JACINTO RIVER WASTE PITS SUPERFUND SITE

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LIST OF ACRONYMS AND ABBREVIATIONS

Anchor Environmental	Anchor Environmental, LLC
Anchor QEA	Anchor QEA, LLC
cfs	cubic feet per second
cm	centimeter
D_{50}	median particle diameter
FS	Feasibility Study
HSC	Houston Ship Channel
IC	institutional control
Integral	Integral Consulting Inc.
MNR	monitored natural recovery
MT	metric tons
ng/kg	nanograms per kilogram
NOAA	National Oceanic and Atmospheric Administration
NSR	net sedimentation rate
OCDD	octachlorodibenzo-p-dioxin
PCL	Protective Concentration Level
RI	Remedial Investigation
Site	San Jacinto River Waste Pits Superfund Site
SJRF	San Jacinto River Fleet
S/S	solidification/stabilization
TCDD	2,3,7,8-tetrachlorodibenzo-p-dioxin
TCDF	2,3,7,8-tetrachlorodibenzofuran
TCEQ	Texas Commission on Environmental Quality
TCRA	Time Critical Removal Action
TEQ	toxicity equivalent
TMDL	total maximum daily load
TOC	total organic carbon
USEPA	U.S. Environmental Protection Agency
WSE	water surface elevation

1 INTRODUCTION

This appendix to the Draft Final Interim Feasibility Study (FS) Report for the San Jacinto River Waste Pits Superfund Site (Site) describes chemical fate and transport modeling that was performed in support of the FS. The models used in this effort are summarized in Section 1.1, and the specific evaluations conducted for the FS are introduced in Section 1.2.

1.1 Background on the Chemical Fate and Transport Modeling Study

The Chemical Fate and Transport Modeling Study report (Anchor QEA 2012a) was submitted for U.S. Environmental Protection Agency (USEPA) review in February 2012, and USEPA comments were addressed in a draft final report submitted on July 18, 2012. USEPA approved the report with certain modifications in a letter dated September 12, 2012 (Miller 2012, pers. comm.).[1] The document was modified accordingly, and the final report was submitted to USEPA on October 11, 2012 (Anchor QEA 2012a).

1.1.1 Study Objectives

The primary goal of the Chemical Fate and Transport Modeling Study (Anchor QEA 2012a) was to simulate physical and chemical processes governing chemical fate and transport of selected dioxins and furans in the aquatic environment within the USEPA's Preliminary Site Perimeter[2], which is shown on Figure 1-1. The primary objectives of the chemical fate and transport analysis were three-fold, as follows:

- Develop conceptual site models for sediment transport and chemical fate and transport
- Develop and apply quantitative methods (i.e., computer models) that can be used to evaluate the effectiveness of various remedial alternatives during the FS
- Address specific questions about sediment transport and chemical fate and transport processes within the USEPA's Preliminary Site Perimeter

[1] In that letter, USEPA also required that additional model sensitivity analyses be performed as part of the FS. Those sensitivity analyses were conducted and are described in Section 2 of this Appendix.

[2] The term "USEPA's Preliminary Site Perimeter" refers to the area shown within the "preliminary perimeter" in Appendix B of the Unilateral Administrative Order (USEPA 2009).

Any model has some amount of uncertainty associated with its predictions due to various assumptions that need to be made during its development and/or data limitations; because of this uncertainty, results from the chemical fate and transport modeling are used in the FS to provide relative comparisons between the outcomes of the various remedial alternatives being evaluated (models are best used on a relative basis, because most sources of uncertainty are common to all scenarios). Specific predictions of chemical concentrations in sediment and water do not represent actual measures of sediment or water quality during the time period being modeled.

1.1.2 Model Framework and Model Study Area

The fate and transport modeling is based on three linked models that simulate hydrodynamics, sediment transport, and chemical fate and transport (Figure 1-2). The hydrodynamic model simulates temporal and spatial changes in water depth, current velocity, and bed shear stress in the San Jacinto River. This information is transferred from the hydrodynamic model to the sediment transport model, which is used to simulate the erosion, deposition, and transport of sediment in the San Jacinto River. The sediment transport model is used to simulate temporal and spatial changes in suspended sediment concentrations in the water column and bed elevation changes (i.e., bed scour depth and net sedimentation rate [NSR]). The results from the hydrodynamic and sediment transport models are transferred to the chemical fate and transport model, which calculates spatial and temporal variations of dioxin and furan concentrations in the water column and sediment bed. Specifically, the chemical fate processes represented by the model include the following:

- *Sediment-water interactions* – Particulate-associated dioxins and furans within the sediment bed enter the water column in cases where erosion of the surface layer occurs, and chemicals being transported in the water column can likewise deposit on the bed.
- *Partitioning and dissolved phase flux* – Dioxins and furans within the surface layer of the sediment bed are also present in the dissolved phase due to partitioning processes. In some cases, the resulting porewater concentrations can be greater than those in the overlying water column. Such a concentration gradient, through the process of surface exchange flux (due to diffusion, bioturbation, and tidal pumping), can result in

a transfer of dissolved-phase mass to the water column that in turn can affect concentrations in the river under low-flow conditions.

- *Transport in the water column* – Dissolved and particulate phase dioxins and furans that are present in the water column from a variety of sources, including atmospheric deposition, upstream sources, point sources such as waste water treatment outfalls, and sediments within the area, are transported with the currents, which are affected by freshwater flow in addition to more complex circulation patterns associated with the tides.
- *Inputs from external sources* – As described above, dioxins and furans can enter the aquatic environment from the sediment bed and external sources. The Texas Commission on Environmental Quality's dioxin Total Maximum Daily Load (TMDL) study[3] (University of Houston and Parsons 2006) detected dioxins and furans in samples of outfalls and surface runoff, and in dry and wet atmospheric deposition samples that were collected adjacent to the San Jacinto River and in areas within the USEPA's Preliminary Site Perimeter. These inputs represent external sources to the area, referred to below as the Model Study Area, and are accounted for and reflected in the results of the fate and transport modeling presented below.

The model's predictions reflect the processes described above using a mass balance approach; as such, its predictions of surface water concentrations reflect sources from upstream, point and non-point sources, flux from sediments, and transport throughout the Model Study Area.

For the purposes of chemical fate and transport modeling, the Model Study Area is defined as the San Jacinto River from the Lake Houston Dam to the Houston Ship Channel (HSC; Figure 1-1). This Model Study Area was selected so that appropriate boundary conditions are utilized in the numerical models, which was needed to produce reliable predictions within the USEPA's Preliminary Site Perimeter.[4] The resolution of model grid cells is spatially variable, with high resolution (i.e., smaller grid cells) in the region near the impoundments north of Interstate 10 (Northern Impoundments), which is the area that underwent a Time Critical Removal Action (TCRA) and is hereafter referred to as the TCRA Site.

[3] http://www.tceq.texas.gov/waterquality/tmdl/26-hscdioxin.html

[4] The hydrodynamic model also simulates a portion of the HSC in order to properly represent tidal exchange at the confluence with the San Jacinto River (see Anchor QEA 2012a for details).

1.1.3 Model Development and Calibration

Model development and calibration was described in the Chemical Fate and Transport Modeling Study report (Anchor QEA 2012a). A brief summary is provided below.

Development of the hydrodynamic model consisted of specifying the following inputs: 1) bathymetry and geometry; 2) freshwater inflow at the upstream boundary at the Lake Houston Dam; 3) freshwater inflow at the various bayous discharging into the simulated portion of the HSC; and 4) water surface elevation (WSE) at the downstream boundary (i.e., near the confluence of the San Jacinto River and the HSC). Data obtained from historical sources or collected as part of this study were used to determine these model inputs. The hydrodynamic model was calibrated using current velocity and WSE data collected at two locations in the Model Study Area during 2010 and 2011. Daily average WSE data collected at the U.S. 90 Bridge during a 14-year period (1997 to 2010) were used for additional validation of model performance over a wide range of flow conditions in the river. Overall, the calibration and validation results demonstrate that the model is able to sufficiently simulate the hydrodynamics within the Model Study Area to meet the objectives of this study.

The sediment transport model was developed based on Model Study Area-specific information on sediment properties (e.g., grain size distribution, bulk density), bed properties (e.g., mapping of cohesive and non-cohesive bed areas), and boundary conditions (e.g., sediment load passing Lake Houston Dam and incoming load during flood tide at the downstream boundary near the confluence of the San Jacinto River and the HSC). The calibration period for the sediment transport model was the 21-year period from 1990 through 2010. The sediment transport model was calibrated to measurements of long-term NSR estimated from radioisotope cores collected at ten locations within the Model Study Area. Overall, the report concluded that the model predicted NSRs with reasonable accuracy. The general pattern of net sedimentation predicted by the model is qualitatively consistent with known characteristics of the Model Study Area. At small spatial scales (e.g., single grid cell), the model uncertainty is higher; however, as the spatial scale increases, the uncertainty in the model's predictive capability decreases. This trend (i.e., decreasing uncertainty in model reliability with increasing spatial scale) is consistent with sediment transport models developed at other sites that have been successfully calibrated and used as a management tool.

The chemical fate and transport model was developed for three dioxin and furan congeners (2,3,7,8-tetrachlorodibenzo-p-dioxin [TCDD], 2,3,7,8-tetrachlorodibenzofuran [TCDF], and octachlorodibenzo-p-dioxin [OCDD]). Parameters describing the various processes simulated by the fate model (described above) were developed based on available Model Study Area data (e.g., dioxin and furan concentrations in sediment and surface water), information generated as part of the TMDL study (e.g., loads associated with permitted outfalls, atmospheric deposition, and surface runoff), and literature (e.g., depth and rate of sediment bioturbation and surface porewater exchange coefficients). The chemical fate model was developed and calibrated using surface water and sediment bed data collected between 2002 and 2010 prior to the TCRA; the number of samples is summarized in Table 1-1 below.

Table 1-1
Summary of Water Column and Sediment Data Used to Develop and Calibrate Fate and Transport Model

Program	Years	Number of Locations	Number of Samples
TMDL surface water[1]	2002 – 2004	6[2]	34[2]
TCEQ surface water	2009	2[2]	3[2]
TMDL sediment	2002 – 2005	70	70
TCEQ et al. sediment[3]	2009	18	19
RI sediment	2010	162	170

Notes:
[1] Each TMDL water column sample was analyzed separately for dissolved- and particulate-phase dioxins/furans.
[2] Only one of the TMDL surface water sample locations (nine total samples) was located within the USEPA's Preliminary Site Perimeter (but from a location outside the perimeter of the Northern Impoundments). The 2009 TCEQ surface water samples were all collected from within the perimeter of the Northern Impoundments. As shown in the table above, the data available for surface water were more limited than those for sediment, especially post-2004.
[3] 2009 sediment data were collected by TCEQ and others
RI – Remedial Investigation
TCEQ – Texas Commission on Environmental Quality
TMDL – total maximum daily load

The chemical fate model was shown to provide a good representation of spatial gradients in water column dioxin and furan concentrations (on a whole-water basis) across the Model Study Area.[5] The model also simulated the spatial patterns and differences between particulate- and dissolved-phase water column concentrations within the Model Study Area. With respect to surface sediment concentrations, for which much more empirical data are available for comparison (Table 1-1), the chemical fate model predicted a decline in surface sediment concentrations within the area surrounding the USEPA's Preliminary Site Perimeter over the period from 2005 to 2010 that is within a factor of 2.5 of the decline estimated from data-based evaluations presented in the *Chemicals of Potential Concern Technical Memorandum* (Integral 2011); these results are considered consistent when uncertainties associated with both the data and model are taken into account.

Overall, the modeling framework summarized above provides a useful management tool for evaluating remedial alternatives in the FS. It integrates the large body of Model Study Area data into a quantitative, objective framework. The models were calibrated to several datasets covering varying spatial and temporal scales, and were shown to provide a good representation of hydrodynamics, sediment transport, and chemical fate and transport within the Model Study Area, subject to the above-described data limitations.

It should be noted that the model summarized above was developed and calibrated based on data collected prior to implementation of the TCRA in 2010 and 2011. The TCRA was implemented to stabilize soils/sediments within the original 1966 perimeter berm of the TCRA Site to prevent the release of dioxins and furans and other chemicals of potential concern to the environment (Anchor QEA 2011a) by installation of an armor rock cap that in most areas was placed atop a geotextile bedding layer (as well as a geomembrane cover layer in certain portions of the area). The effect of the TCRA on fate and transport of dioxins and furans in the Model Study Area was evaluated by the modeling presented in this appendix.

[5] Model predictions of water concentrations are not equivalent to actual measurements, and verification of model predictions is limited by data availability as noted above.

1.2 Application of the Model in the Feasibility Study

As part of the FS, the model was used to develop estimates of future dioxin and furan concentrations in sediment and surface water within the Model Study Area. The specific FS model applications presented in this appendix include the following:

- Long-term future simulations were first conducted for current (post-TCRA) conditions (i.e., starting from contemporary sediment concentrations within the USEPA's Preliminary Site Perimeter, and reflecting the presence of the Armored Cap [as described in the FS] at the TCRA Site). These simulations served two purposes for the FS. First, the model was used to provide estimates of the effects of the TCRA on surface water concentrations of select dioxin and furan congeners within the Model Study Area. Second, these simulations also provide estimates of rates of natural recovery (i.e., reductions in surface sediment dioxin and furan concentrations over time) in various portions of the Model Study Area in the absence of any remedial action beyond the current Armored Cap. These simulations, therefore, apply to the No Further Action alternative (Alternative 1N), as well as two other alternatives evaluated in the FS: i) Alternative 2N (institutional controls [ICs] and monitored natural recovery [MNR]); and ii) Alternative 3N (ICs and MNR plus construction of enhancements to the Armored Cap [as described in the FS] to create the Permanent Cap [Permanent Cap]). For both of these evaluations (i.e., predictions of the effects of the TCRA on surface water concentrations and predictions of natural recovery rates), simulations were also conducted with alternate sets of model input parameters to develop uncertainty bounds on the predictions.
- Simulations were also conducted of Alternatives 4N, 5N, 5aN, and 6N, which include active remediation of soil/sediments within the TCRA Site, as well as sediments exceeding Protective Concentration Levels (PCLs) from another area within the USEPA's Preliminary Site Perimeter in the case of Alternative 6N. In addition to evaluating general long-term trends for these alternatives, the model's predictions of relative future sediment and water column dioxin and furan concentrations from these simulations were also used to quantify potential short- and long-term impacts associated with the construction activities (i.e., sediment resuspension and release during remediation and effects of dredge residuals).

1.3 Appendix Organization

The remainder of this appendix is organized as follows. Section 2 describes sensitivity analyses that were performed with the hydrodynamic and sediment transport models at the request of USEPA in its letter approving the draft final Chemical Fate and Transport Modeling Study report (Miller 2012, pers. comm.). Section 3 presents long-term simulations of post-TCRA future conditions conducted with the model, including a discussion of the model setup, model results, and uncertainty analyses associated with use of the model to: 1) evaluate the impacts of the TCRA on estimated surface water concentrations; and 2) predict future surface sediment concentrations and estimated rates of natural recovery. Section 4 documents the model simulations used to evaluate the remedial alternatives; it compares the estimated rates of natural recovery from the post-TCRA future simulation, which is representative of Alternatives 1N through 3N, with results from model simulations of the active soil/sediment remediation alternatives (Alternatives 4N through 6N). A summary of this appendix is presented in Section 5, and reference citations are contained in Section 6.

2 HYDRODYNAMIC AND SEDIMENT TRANSPORT MODEL SENSITIVITY ANALYSES

In response to USEPA's request for additional hydrodynamic and sediment transport model sensitivity analyses in its conditional approval letter for the draft final Chemical Fate and Transport Modeling Study report (Miller 2012, pers. comm.), a series of simulations was conducted to evaluate: 1) sediment deposition and erosion during high-flow events; and 2) the sensitivity of model predictions to WSE at the downstream boundary.

2.1 Evaluation of Deposition and Erosion During High-Flow Events

The calibrated hydrodynamic and sediment transport models (Anchor QEA 2012a) were used to simulate sediment transport processes in the San Jacinto River during high-flow events. A range of high-flow conditions, from 2- to 100-year events, were investigated, with the objective of answering the following questions:

- What portions of the Model Study Area are depositional and what areas experience erosion during a given high-flow event?
- What are the depths of net deposition and erosion during a given high-flow event?

High-flow events with return periods of 2, 10, and 100 years were evaluated during this analysis. The probability of a high-flow event occurring in any given year is 50 percent, 10 percent, and 1 percent for return periods of 2, 10, and 100 years, respectively. Peak flow rates at Lake Houston Dam for the three high-flow events evaluated in this analysis are listed in Table 2-1. The peak flow rates for these flood simulations were determined from a flood frequency analysis that was performed using historical flow rate data collected at Lake Houston Dam (see Section 3.3.1 of Anchor QEA 2012a). Incoming sediment loads to the San Jacinto River at the dam during the flood simulations were estimated using the methodology described in Section 4.2.3 of Anchor QEA (2012a).

Table 2-1
Peak Flow Rates and Sediment Loads at Lake Houston Dam for High-Flow Event Simulations

Return Period (years)	Peak Flow Rate (cfs)	Total Sediment Load (MT)
2	38,400	56,600
10	126,000	324,000
100	372,000	1,620,000

Notes:
cfs – cubic feet per second
MT – metric tons

Simulating sediment transport in the San Jacinto River during a high-flow event requires specifying time-variable inflow at both the Lake Houston Dam and the HSC boundary tributaries (i.e., high-flow hydrographs). At the Lake Houston Dam inflow boundary, the hydrograph that occurred during the high-flow event in October 1994 was chosen. This flood had a peak flow rate of approximately 356,000 cubic feet per second (cfs) measured in the San Jacinto River at the U.S. Geological Survey gauging station located at the U.S. 90 Bridge near Sheldon, Texas, representing a return period of between 50 and 100 years. The October 1994 event was selected for this analysis, as opposed to other high flow events that occurred in the area, because this event was: 1) the highest flow rate during the 21-year period used for sediment transport model calibration (1990 through 2010); and 2) similar in magnitude (i.e., only 4.5 percent lower) to the flow rate for the 100-year flood (372,000 cfs). The hydrographs for the specific high-flow events evaluated in this analysis (i.e., 2-, 10-, and 100-year events) were developed by linearly scaling the October 1994 hydrograph so that the peak flow rate corresponded to the appropriate value for each event (i.e., those listed in Table 2-1). For example, the hydrograph for the 100-year event was generated by increasing the peak flow rate during the October 1994 event by 4.5 percent. For the hydrographs of the HSC tributaries, observed time-variable flow rates during the October 1994 flood period were used as model input. This assumption was evaluated in a sensitivity analysis by comparing the results to those using the average flow rates for each of the tributaries.

Temporal variation in WSE at the downstream boundary for these simulations was specified using data collected during the October 1994 high-flow event at the National Oceanic and Atmospheric Administration (NOAA) tidal gauge station at Morgan's Point. Time histories of flow rate at Lake Houston Dam (top panel) and WSE at the downstream boundary (bottom panel) during the high-flow event simulations are shown on Figure 2-1. The WSE shown on this figure represents the WSE corresponding to the 100-year event (i.e., measured at Morgan's Point during the October 1994 event); this same WSE was used for the downstream boundary for the 2- and 10-year event simulations, because flow rate has more of an effect on predicted velocities and net sedimentation within the USEPA's Preliminary Site Perimeter than the downstream boundary WSE.

Spatial distributions of predicted net erosion and deposition at the end of the 2-year high-flow simulation are shown on Figures 2-2 and 2-3, respectively. During the 2-year high-flow event, net erosion was predicted to occur only in 6 percent of the total bed area in the Model Study Area and over just 8 percent of the area within the USEPA's Preliminary Site Perimeter,[6] with bed scour being predicted to occur primarily in the sub-tidal zone. Predicted net erosion depths in these limited areas were all less than -3 centimeters (cm), with average and maximum predicted net erosion depths of -0.5 and -2.3 cm, respectively, within the USEPA's Preliminary Site Perimeter during the 2-year flood. Within the USEPA's Preliminary Site Perimeter, the average and maximum net deposition values were predicted to be 0.1 and 1.9 cm, respectively, during the 2-year high-flow event (Table 2-2).

During the 10-year high-flow event, net erosion was predicted over a larger area, although most of the net erosion depths were predicted to be less than -5 cm; there were a few isolated areas with erosion depths predicted to range between -5 and -8 cm. Spatial distributions of predicted net erosion and deposition for the 10-year flood simulation are presented on Figures 2-4 and 2-5, respectively. Average values of predicted net erosion and deposition within the corresponding portions of the USEPA's Preliminary Site Perimeter were -2.1 and 0.7 cm, respectively, during the 10-year flood (Table 2-2). Maximum values of bed scour and deposition were -7.7 and 9.9 cm, respectively, within that area. Over the entire Model Study Area, net deposition was predicted to occur in 73 percent of the bed area, with net erosion predicted in 27 percent of the area. The fractions of bed area predicted to experience net deposition and net erosion within the USEPA's Preliminary Site Perimeter during the 10-year event were 54 percent and 46 percent, respectively.

[6] Total area for the Model Study Area and USEPA's Preliminary Site Perimeter is 4,023 acres and 900 acres, respectively.

Spatial distributions of predicted net erosion and deposition at the end of the 100-year high-flow simulation are shown on Figures 2-6 and 2-7, respectively. Net erosion was predicted in 45 percent of the bed area in the Model Study Area (with the remaining 55 percent being net depositional) and 56 percent of the area within the USEPA's Preliminary Site Perimeter. During the simulated 100-year flood, the average and maximum values of predicted net deposition within the USEPA's Preliminary Site Perimeter were 2.6 and 26 cm, respectively (Table 2-2). The average and maximum predicted scour depths were -4.5 and -29 cm, respectively, within the USEPA's Preliminary Site Perimeter; scour depths greater than 10 cm were predicted to occur in less than 5 percent of that area.

Table 2-2
Predicted Bed Elevation Change within the USEPA's Preliminary Site Perimeter for High-Flow Event Simulations

Return Period (years)	Average Net Deposition (cm)	Maximum Net Deposition (cm)	Average Net Erosion (cm)	Maximum Net Erosion (cm)
2	0.1	1.9	-0.5	-2.3
10	0.7	9.9	-2.1	-7.7
100	2.6	26	-4.5	-29

Notes:
cm – centimeters

Results of the high-flow event simulations described above are representative of conditions immediately after the occurrence of those floods. The post-flood conditions will change with time as sediment is transported into the Model Study Area during lower flow conditions (i.e., deposition will occur in areas that experience bed scour during floods). This type of recovery process after a major flood was incorporated into the long-term 21-year sediment transport calibration simulation (Anchor QEA 2012a). The results from those simulations indicated that the area within the USEPA's Preliminary Site Perimeter is net depositional on a long-term basis (i.e., throughout the 21-year simulation presented in Anchor QEA [2012a]).

2.2 Sensitivity Analysis: Water Surface Elevation at Downstream Boundary

Data collected at the Morgan's Point tidal gauge station were used to specify WSE at the downstream boundary of the hydrodynamic model because of gaps in the data records of the

Battleship Texas State Park and Lynchburg gauge stations. An analysis of differences between WSE data collected at the Battleship Texas State Park/Lynchburg and Morgan's Point gauge stations was presented in Anchor QEA (2012a). The effects of data source for specifying WSE at the downstream boundary of the model were evaluated by simulating hydrodynamic conditions from 2002 using data collected at the Lynchburg gauge station (Anchor QEA 2012a). USEPA requested that a similar analysis be conducted using WSE data collected during 2001 (Miller 2012, pers. comm.). Comparisons of WSE data collected at the Morgan's Point and Lynchburg tidal gauge stations during 2001 are shown on Figure 2-8. These data show WSE was very consistent between the two stations in 2001. The only significant differences in WSE between the two locations occurred in early June 2001, during a flood on the San Jacinto River; this flood had a peak flow rate that corresponded to a return period between 2 and 10 years. The WSE measured at Morgan's Point during that event were lower than those measured at the Lynchburg station.

The models were used to simulate hydrodynamics and sediment transport during 2001, with the downstream boundary condition specified using WSE data collected at the Lynchburg tidal gauge station. These results were compared to the original (base case) simulation for 2001, for which the downstream boundary condition was specified using WSE data collected at the Morgan's Point tidal gauge station. Cumulative frequency distributions of predicted bed elevation changes for grid cells within the USEPA's Preliminary Site Perimeter for the base case (Morgan's Point) and sensitivity (Lynchburg) simulations are compared on Figure 2-9. Differences in bed elevation change between the two simulations range between -2 and +1 cm for the grid cells within the USEPA's Preliminary Site Perimeter (Figure 2-9, bottom panel). These results are similar to the previous analysis conducted for 2002 (Anchor QEA 2012a). A one-to-one comparison of bed elevation changes for each model grid cell within the USEPA's Preliminary Site Perimeter is presented on Figure 2-10; this figure also demonstrates the minimal difference between the base case and sensitivity simulations. Overall, the data source for specifying WSE at the downstream boundary of the hydrodynamic model has minimal effect on sediment transport within the USEPA's Preliminary Site Perimeter.

3 SIMULATION OF POST-TCRA FUTURE CONDITIONS

As noted in Section 1.1.3, the calibrated model described in Anchor QEA (2012a) was developed based on data collected prior to placement of the Armored Cap in 2010 and 2011. As such, the model was first updated to reflect current conditions, which include the presence of the Armored Cap over the TCRA Site. Long-term future simulations under these post-TCRA conditions were then conducted using the updated model. These simulations were used to provide estimates of future rates of natural recovery (i.e., reductions in water column and surface sediment dioxin and furan concentrations over time) in various portions of the Model Study Area. The subsections below describe the methods used to develop these long-term simulations, and the results from the model evaluations of TCRA impacts on relative surface water concentrations and model-predicted rates of natural recovery in sediments.

Because any model has some amount of uncertainty associated with its predictions (due to uncertainty in certain model inputs and assumptions, as well as data limitations), it is often desirable to quantify that uncertainty so that it can be factored into the interpretation of model predictions, as well as any decisions that may be made based on the results. Therefore, this section also describes an analysis of uncertainty that involved conducting simulations based on alternate sets of input parameters, for both sediment transport and chemical fate. Specifically, the uncertainty analysis results associated with the sediment transport model, and the chemical fate model's predictions of the effects of the TCRA on surface water dioxin/furan concentrations and future natural recovery rates in sediments are described. In some cases, the uncertainty associated with certain model assumptions may be difficult to quantify. While these uncertainties exist, they do not hinder the model's ability to evaluate scenarios on a comparative (relative) basis, because such sources of uncertainty are common to all scenarios.

3.1 Hydrodynamic and Sediment Transport Models

3.1.1 Model Setup

3.1.1.1 General Setup of Long-Term Simulation

The long-term, 21-year hydrodynamic and sediment transport simulations used for calibration of the sediment transport model (Anchor QEA 2012a) were updated to represent conditions present in the TCRA Site after implementation of the TCRA for the purposes of future simulations; this period is referred to hereafter as the Future Projection Period. The basis of design for the Armored Cap was the construction of a cap designed to withstand a flow event with a return period of 100 years. The area that was affected is shown on Figure 3-1. Model inputs were revised to reflect physical conditions after construction of the Armored Cap, with the following changes made within the TCRA Site:

- Bed elevations were updated to reflect the increase in elevation due to the Armored Cap.
- The sediment bed map was revised to reflect the placement of the Armored Cap, which is composed of armor stone, and, therefore, represented as non-cohesive sediment in the model.
- The median particle diameter (D_{50}) was updated to represent the armor stone size of the Armored Cap.

Updated bed elevation inputs were based on an interpolated surface map created from data collected during October 2012 by Hydrographic Consultants Limited, which was representative of post-TCRA construction conditions. Pre- and post-TCRA bathymetry and topography data are compared on Figure 3-1. Increases in bed elevation due to the Armored Cap placement (i.e., post-TCRA construction) are evident within the TCRA Site on this figure.

The sediment bed map for the model grid cells within the TCRA Site was converted from cohesive to non-cohesive sediment, as shown on Figure 3-2. The model's median particle diameter in the TCRA Site was also updated using cover material gradation data provided in the Final Removal Action Work Plan (Anchor QEA 2011b). Each zone within the TCRA Site received a specific cap material type; a summary of those zones is shown in Table 3-1, and a comparison of the changes to the median particle diameter used in the model to reflect these cap types is shown on Figure 3-3.

Table 3-1
Cover Material Gradation of the Armored Cap

Material Designation Zone	Material Type	Median Particle Diameter: D_{50} (inches)
Cap A	Recycled concrete	3
Cap B/C	Recycled concrete	6
Cap C	Natural stone	6
Cap D	Natural stone	8

3.1.1.2 Uncertainty Analysis

Uncertainty exists in the predictions of the sediment transport model because of uncertainty in model inputs and assumptions. Although some uncertainties are difficult to quantify, the effects of uncertainty in key model inputs on the long-term sediment transport model calibration were previously evaluated through a quantitative sensitivity analysis, as documented in Section 4.4.1 of Anchor QEA (2012a). Specifically, the effects of varying the following model inputs were evaluated: 1) erosion rate parameters; 2) incoming sediment load at the Lake Houston Dam;[7] and 3) effective bed roughness. To evaluate the effects of possible interactions between the three inputs, a factorial analysis was conducted, which resulted in eight simulations to account for all of the possible combinations of the bounding limits of the three inputs. The parameter sets used in the eight sensitivity simulations are provided in Table 3-2, where "lower" refers to lower-bound value and "upper" refers to upper-bound value. The effects of each sensitivity simulation were evaluated through comparison to the base case simulation results. A more detailed description of this sensitivity analysis is provided in Section 4.4.1 of Anchor QEA (2012a). These same sensitivity analysis simulations were repeated for the post-TCRA conditions model setup.

[7] As described in Anchor QEA (2012a), the incoming sediment load was varied by ± a factor of 2 with respect to that used for the base model calibration. A factor of 2 was selected for the sensitivity analysis to understand the model response to changes in the upstream load, while also maintaining fidelity to the model calibration (i.e., increases beyond a factor of 2 would result in the model being out of calibration with respect to the NSR data).

Table 3-2
Bounding Limits for Sediment Transport Model Sensitivity Analysis

Sensitivity Simulation	Upstream Sediment Load	Effective Bed Roughness	Erosion Rate Parameters
1	Lower	Lower	Lower
2	Lower	Lower	Upper
3	Lower	Upper	Lower
4	Lower	Upper	Upper
5	Upper	Lower	Lower
6	Upper	Lower	Upper
7	Upper	Upper	Lower
8	Upper	Upper	Upper

3.1.2 Results

Spatial distributions of predicted NSRs for the long-term simulation period for pre- (i.e., the sediment transport model calibration) and post-TCRA conditions are shown on Figures 3-4 and 3-5, respectively. Generally, the model predicted slightly more deposition to occur within the TCRA Site for the post-TCRA case; otherwise, differences in NSR between the two cases are minimal. Spatial distributions of predicted net erosion rate for pre- and post-TCRA conditions are presented on Figures 3-6 and 3-7, respectively. Areas of net erosion are similar for the two cases.

To evaluate the uncertainty of these sediment transport model predictions, comparisons of model-predicted and empirically estimated NSR values are shown on Figure 3-8. On that figure, each cross-hatched box represents the range of NSR values based on lower- and upper-bound estimates of the data, and the whisker bars correspond to the uncertainty range in NSR due to uncertainty in laboratory analytical results. The model-predicted NSR values (shown as different colored circles representing the base case post-TCRA future simulation and the various sensitivity simulations) represent average values during the Future Projection Period. This Future Projection Period included a rare flood (i.e., approximately 100-year return period, as discussed in Section 2.1) that was predicted to have a significant effect on the Model Study Area, which may bias the model predictions of NSR to some extent due to its inclusion in the simulation period (i.e., unrealistic decrease of NSR; see Anchor QEA [2012a]). Thus, model predictions for the 16-year period corresponding to flows from 1995 through 2010 are also compared to the empirically estimated NSR values. Similar comparisons of predicted and estimated NSR for the 16-year period from 1995 through 2010 are shown on Figure 3-9. Overall, these figures show that the range of sensitivity simulations result in predicted values for NSR that are within approximately a factor of 2 of the base case calibration, which in many cases is consistent with the range of uncertainty in the empirical data.

Results of the sensitivity simulations for post-TCRA conditions were also evaluated using a sediment mass balance for the Model Study Area as a metric for quantitative comparison. The sensitivity of the predicted trapping efficiency for the Model Study Area to varying the three model inputs is shown on Figure 3-10. The base case trapping efficiency predicted by the model was 17 percent, with the range of trapping efficiencies for the sensitivity simulations being 6 percent to 24 percent.[8] These results are very similar to the sensitivity analysis results for the pre-TCRA condition (Anchor QEA 2012a).

Rates of gross erosion, gross deposition, and net deposition and erosion for the base case and each of the sensitivity simulations predicted within the USEPA's Preliminary Site Perimeter are compared on Figure 3-11. Gross erosion rate was the total sediment mass eroded from all grid cells that were predicted to be erosional (i.e., bed scour) during the Future Projection Period within the USEPA's Preliminary Site Perimeter. Similarly, gross deposition rate was the total sediment mass deposited in all grid cells that were predicted to be depositional during the Future Projection Period. Rate of net change (i.e., either net deposition or erosion) was the difference between gross deposition and gross erosion (i.e., rate of change equals gross deposition minus gross erosion, with positive values being net deposition and negative values being net erosion). Overall, the sensitivity analyses result in a range in gross erosion and deposition rates that are within a factor of 2 to 3 of the base case.

Based on the results described above, sediment transport Sensitivity Simulations 2 and 7 were selected as lower- and upper-bound parameter sets to be carried forward to the evaluation of fate and transport model uncertainty (described below). The lower-bound parameter set produced the minimum trapping efficiency within the Model Study Area

[8] Simulation 4 was net erosional, so no trapping efficiency was calculated for that simulation.

(Figure 3-10), as well as the minimum net deposition rate within the USEPA's Preliminary Site Perimeter (Figure 3-11). In contrast, the upper-bound parameter set produced the second highest values of trapping efficiency within the Model Study Area (Figure 3-10) and net deposition rate within the USEPA's Preliminary Site Perimeter (Figure 3-11). Predicted NSRs within the USEPA's Preliminary Site Perimeter for these lower- and upper-bound parameter sets were in reasonable agreement with the range of measured values (Figures 3-8 and 3-9).

3.2 Chemical Fate and Transport Model

3.2.1 Model Setup

3.2.1.1 General Setup of Long-Term Simulations

As described in Anchor QEA (2012a), the chemical fate and transport model was calibrated over the 6-year period between 2005 and 2010. For the long-term future simulations conducted for the FS, the fate and transport model also used the Future Projection Period (i.e., this forecast was based on the 21-year flow and tide history used for the hydrodynamic and sediment transport models described above). These simulations were developed to predict future dioxin/furan concentrations to support relative comparisons of remedial alternatives; the historical hydrodynamic information used to project conditions during the Future Projection Period was only used as a means of estimating future flow and tide conditions in the river (i.e., this makes the reasonable assumption that flows in the future will be statistically similar to those observed in the past).

In addition, the sediment dioxin/furan concentrations in the model were revised for the simulations of post-TCRA future conditions. As described in Anchor QEA (2012a), the initial sediment concentrations specified in the model for calibration were based on concentrations of dioxins and furans in sediment collected within the Model Study Area in 2002 to 2005. For the future simulations described in this section, the sediment dioxin/furan initial concentrations in the model were updated using the 2010 to 2012 Remedial Investigation (RI) Report sediment dataset (Integral and Anchor QEA 2013). This dataset provides a more detailed characterization of contemporary dioxin/furan sediment concentrations within the USEPA's Preliminary Site Perimeter. The methodology used to develop surface sediment dioxin/furan initial conditions was generally the same as that described in Section 5.2.5.2 of Anchor QEA (2012a)—i.e., Thiessen polygons were generated for all sediment sample locations and mapped onto the model grid. However, in the area of the TCRA Site, the Thiessen polygons were generated consistent with the methodology used in the Remedial Alternatives Memorandum (Anchor QEA 2012b), whereby the polygons were generated separately for the areas within and outside the TCRA Site boundary. To simulate future (i.e., post-placement of the Armored Cap) conditions, the sediment dioxin/furan concentrations were set to zero in the grid cells corresponding to the TCRA Site. This setting in the model corresponds to the assumption of no release of dioxins/furans from that area to the overlying water column, consistent with the data collected during the Armored Cap Porewater Assessment (see Section 5.3 of the RI Report). However, the post-TCRA model simulation results (described below) show that the surface of the Armored Cap equilibrates with sediments from the surrounding area over time because of transport and deposition of dioxin-bearing sediments from upstream areas. As discussed above, to evaluate the impacts of the TCRA on relative surface water conditions, a second comparison simulation was conducted based on pre-TCRA sediment conditions; for this simulation, the surface sediment concentrations within the TCRA Site were based on RI samples collected from that area. Figures 3-12a and 3-12b present the Thiessen polygons within the USEPA's Preliminary Site Perimeter developed based on the 2010 to 2012 RI data used for these two simulations for TCDD and TCDF, respectively.

Similar to the sediment initial conditions, sediment total organic carbon (TOC) in the model was updated based on the 2010 to 2012 RI dataset. A map showing the updated model TOC is provided on Figure 3-13. All other chemical fate model inputs (i.e., boundary conditions, external loads, partition coefficients, mass transfer coefficients) used in the post-TCRA future simulations were the same as those from the calibrated model (Anchor QEA 2012a).

3.2.1.2 Uncertainty Analysis

Similar to the sediment transport model uncertainty analysis described above, the effects of input uncertainty on chemical fate model predictions were previously evaluated through sensitivity analyses conducted as part of the Chemical Fate and Transport Modeling Study (Anchor QEA 2012a). To develop uncertainty analyses for the long-term future modeling for the FS, the two bounding sediment transport simulations described in Section 3.1.1.2 above

(i.e., sediment transport Sensitivity Simulations 2 and 7) were propagated through the fate model uncertainty simulations and combined with two bounding chemical fate and transport input parameter sets. The sets of bounding parameters for the fate and transport model used in this uncertainty analysis were those from the combined parameter sensitivity analysis described in Section 5.3.3.2.7 of Anchor QEA (2012a). For that sensitivity analysis, values related to bed mixing (i.e., depth and rate of bioturbation), the downstream boundary condition (i.e., estimated dioxin/furan concentrations in surface water at HSC), and partition coefficients were modified (Anchor QEA 2012a). The goal of these simulations was to produce upper-bound and lower-bound results to quantify the uncertainty range associated with the model's base case future predictions. Because different combinations of chemical fate model parameters, when coupled with the two bounding sediment transport model simulations, could produce differing responses in water column and sediment concentrations, all four possible combinations were simulated (i.e., the two bounding sediment transport simulations and two alternate sets of chemical fate parameters).
Table 3-3 lists the combinations of sediment transport and chemical fate model input sets that were used in the uncertainty analysis, and how they are referred to in the discussion of results below.

Table 3-3
Fate Model Uncertainty Simulations

Fate Run Name	Sediment Transport Sensitivity Simulation	Fate Model Parameters		
		Bed Mixing	Downstream Boundary	Partition Coefficient
Fate Uncertainty 1	Simulation 7	None	Decreased	Increased
Fate Uncertainty 2	Simulation 7	Increased	Increased	Decreased
Fate Uncertainty 3	Simulation 2	None	Decreased	Increased
Fate Uncertainty 4	Simulation 2	Increased	Increased	Decreased

3.2.2 Results

3.2.2.1 Water Column

The predicted effects of placement of the Armored Cap on surface water concentrations, including model uncertainty, were evaluated based on a review of pre- and post-TCRA water column concentration estimates for the four fate model uncertainty simulations described above. It was determined that Fate Uncertainty Simulations 1 and 4 produced the largest upper and lower bounds for the water column predictions, respectively. Therefore, all figures discussed in this section include results for six simulations: the base case (shown as solid lines) and Fate Uncertainty Simulations 1 and 4 (shown as dashed lines), each for both pre- and post-TCRA conditions. These model predictions of water quality are useful for relative comparisons of pre- and post-TCRA conditions, as well as conditions under various remedial alternatives (see Section 4) but are not equivalent to empirical measurements. This is why model uncertainty has been characterized and carried through the discussion of results below and model predictions are most appropriately used for comparative purposes on a relative basis.

As described in Section 1.1.3, the chemical fate and transport model was developed for three dioxin and furan congeners (TCDD, TCDF, and OCDD). Pre- and post-TCRA simulations were conducted for TCDD and TCDF but not OCDD; furthermore, to simplify the discussion presented in this appendix, results below are only discussed for TCDD.[9]

A longitudinal profile of annual average, model-predicted water column TCDD concentration estimates, including the model uncertainty bounds (i.e., annual averages for the two uncertainty simulations), is presented on Figures 3-14a and 3-14b. For these figures, model results were averaged using the same methodology as described in Section 5.3.2.1.1 of Anchor QEA (2012a) and are summarized as follows:

- Model results were averaged only for low-flow days, which was defined as flow less than 4,000 cfs over the Lake Houston Dam.[10]

[9] Graphics of model results for TCDF have been included in Attachment 1 to this appendix; TCDF results are not included in the discussion of this appendix because: 1) model results for TCDF were consistent with those for TCDD in all cases; 2) as noted in Anchor QEA (2012a), the fate and transport behavior of TCDF is similar to that of TCDD due to similarities in their chemical characteristics; and 3) TCDF generally contributes to TEQ in smaller proportions than TCDD (Integral and Anchor QEA 2013). Results for OCDD are not presented in this appendix because OCDD was included in the model only to provide added robustness to the calibration (i.e., because OCDD has different chemical characteristics and it exhibits a different spatial pattern across the Model Study Area as compared to TCDD/TCDF [Anchor QEA 2012a]); it is indicative of background dioxin/furan sources within the Model Study Area (Integral and Anchor QEA 2013).

[10] This also only included days in which flow over the Lake Houston Dam was greater than zero; there are often many days throughout each year where there is no freshwater flow over the dam. These zero-flow conditions were excluded from the averaging to be consistent with conditions, during which the sampling data used for model calibration were collected (Anchor QEA 2012a).

- In order to be shown on a one-dimensional longitudinal profile, the model results from the two-dimensional model grid used in the San Jacinto River were averaged laterally (i.e., across the channel), as well as longitudinally at increments ranging generally from 0.1 to 0.5 mile.
- The annual average results shown on Figures 3-14a and 3-14b are for 2 example years of the simulation. Year 11, which is shown on Figure 3-14a, represents a typical low-flow (having a relatively high frequency of days with zero freshwater inflow upstream of Lake Houston Dam) year near the middle of the model simulation. Year 7, which is shown on Figure 3-14b, represents a year exhibiting a relatively higher frequency of days with non-zero freshwater inflow upstream of Lake Houston Dam. Annual average longitudinal profiles of TCDD (and TCDF) for all years of the Future Projection Period have been included in Attachment 1.

As noted by USEPA in its comments on the draft FS, the model-predicted spatial profiles of pre-TCRA TCDD concentrations shown on Figures 3-14a and 3-14b are somewhat different from those shown for the calibrated model and data shown on Figure 5-19 in Anchor QEA (2012a). Reasons for the apparent differences include the following:

- Model results vary considerably over time and space. As noted above, the results shown on Figure 3-14a represent an annual average of a laterally averaged longitudinal profile for 1 year of the simulation (Year 11). Likewise, Figure 3-14b shows a somewhat different annual average longitudinal profile for a different year of the simulation (Year 7). (Annual average longitudinal profiles for all 21 years of the simulation are shown on Figures 1.1-1a through 1.1-1u in Attachment 1 and show considerable year-to-year variability). Much of the variability observed in the model-predicted annual average longitudinal profiles can be attributed to differences in the amount and frequency of days with zero freshwater inflow from Lake Houston Dam in a particular year.
- Figures 3-14a and 3-14b do not show the variability of daily model predictions over time (they only show annual averages for the base case and upper/lower bound uncertainty simulations), nor do they show the spatial variability among the model grid cells included in the lateral averages. To better understand the range of TCDD concentrations predicted by the model within a given year, a longitudinal profile of model-predicted annual average concentrations (including the range of predictions

associated with the base case simulation) in Year 11 is shown on Figure 3-15. Near the TCRA Site, pre-TCRA TCDD concentrations range from 0.03 to 1 ng/L TCDD, which is generally consistent with water column data collected pre-TCRA in this area.

Therefore, the apparent differences in longitudinal profiles between these simulations and the model calibration simulations (Anchor QEA 2012a) are primarily a result of year-to-year differences in flow and spatial variations that are masked by averaging. Nonetheless, these factors do not affect the use of these simulations, since the primary purpose (as stated previously) is to make relative comparisons between the various scenarios (i.e., between pre- and post-TCRA simulations in the case of Figure 3-14).

The base case and uncertainty simulations all show that the largest differences in predicted water column TCDD concentrations between pre- and post-TCRA conditions are generally within the immediate vicinity of the TCRA Site. For a given set of starting sediment concentrations (i.e., pre- or post-TCRA), the uncertainty simulations produce bounds that are within a factor of 2 to 3 of the base case results. Also, when comparing water column concentration estimates in this area between the two cases, the upper-bound (pre- versus post-TCRA) and lower-bound (pre- versus post-TCRA) simulations both show that the post-TCRA results are lower than the pre-TCRA results (similar to the base case results), with differences up to a factor of 2 to 3. Thus, these results show that although there is uncertainty in the exact magnitude of model-predicted concentrations (e.g., a factor of 2 to 3), there is relatively less uncertainty in the predicted relative reductions achieved by the TCRA (i.e., the upper and lower bounds from the uncertainty simulations show reductions in water column concentration estimates as a result of the TCRA that are both consistent with the base case).

To further illustrate differences in model-predicted pre- and post-TCRA water column concentrations, time-series plots of laterally averaged concentration estimates were developed. Figure 3-16 shows model-calculated concentration estimates of TCDD (averaged monthly) over the Future Projection Period at the following five locations:

- Lake Houston Dam

- River Mile[11] 12, which is near the U.S. 90 Bridge
- River Mile 4.5, which is just upstream of the northern limit of the USEPA's Preliminary Site Perimeter
- River Mile 2.5, which transects the TCRA Site
- River Mile -0.5, which is at the confluence between the San Jacinto River and HSC

Time-series plots were also developed to show spatially averaged model results within the USEPA's Preliminary Site Perimeter and within the footprint of the TCRA Site (Figure 3-17). The flow rate over the Lake Houston Dam is shown on the top panel of both figures.[12] Similar to the spatial profiles, these figures show that the relative differences between pre- and post-TCRA water column concentration estimates for both the upper-bound and lower-bound simulations are similar to the base case. When comparing the overall uncertainty ranges for the six simulations, these figures show that at some of the larger spatial scales, the differences between the pre- and post-TCRA simulations are likely within the range of model uncertainty, although at smaller spatial scales, the effects of the TCRA are clearly evident because there is little to no overlap of the uncertainty bounds (e.g., bottom panel of Figure 3-17).[13] These results indicate there is a relatively localized effect of the TCRA on model-predicted water column concentrations.

[11] River mile locations are shown on Figure 1-1.

[12] The hydrographs shown on Figures 3-16 and 3-17 show a notable change in flow variability starting in Year 7 (model Year 7 corresponds to hydrologic conditions in calendar year 1996 from the Future Project Period). The observed change in the flow variability at this time is related to the availability of Lake Houston Dam lake level data; specifically, lake level data post-July 1996 were used to calculate flow rate based on a rating curve of the dam spillway. When the lake water level dropped below the spillway elevation, there was no recorded flow over the Dam (resulting in flows going to zero). To estimate flow rates prior to July 1996 (when lake level data were not available), flow rate data from six USGS gauging stations located on tributaries to Lake Houston were summed and prorated based on the ratio of the drainage areas of the six tributary watersheds and the drainage area of the watershed that drains into Lake Houston. The effect of reservoir storage on flow rate at the dam was not taken into account using this method, so base flow rates were always modeled as greater than zero for the period prior to July 1996. The methodology used for this analysis is described in Section 3.3.1 of Anchor QEA (2012a).

[13] It should be recognized that model uncertainty is generally higher at smaller spatial scales than it is at larger spatial scales (as discussed in Section 1.1.3). Specifically, water column (and sediment results described later) averaged over relatively small scales, such as the TCRA Site, tend to be somewhat more uncertain than results averaged over larger areas, such as USEPA's Preliminary Site Perimeter. That said, results at these smaller scales are presented for relative comparison purposes only.

To summarize the effects of the TCRA on water column concentration estimates, average percent reductions in model-predicted, pre- and post-TCRA water column TCDD concentration estimates were calculated. Percent reductions in model-predicted water column TCDD concentrations were averaged over two timescales: 1) during the first year of the model simulation, and 2) over the entire Future Projection Period. The calculations were made on various spatial scales, consistent with those shown on Figures 3-16 and 3-17 (i.e., spatially averaged over the USEPA's Preliminary Site Perimeter, laterally averaged over the transect at River Mile 2.5 that runs directly through the TCRA Site, spatially averaged over the TCRA Site, and for the grid cell with the peak estimated concentration within the footprint of the TCRA Site). A summary of the predicted improvement in water column concentration (quantified as an estimated percent reduction between the pre- and post-TCRA model simulations) averaged over these various temporal and spatial scales is provided for the base case and Fate Uncertainty Simulations 1 and 4 in Table 3-4 below.

Table 3-4
Summary of Percent Reduction in Water Column TCDD Concentration Estimates

Run	Time Averaging Period	Percent Reduction			
		USEPA's Preliminary Site Perimeter	River Mile 2.5	TCRA Site	Peak Concentration
Base Case	Year 1	38	74	88	87
Fate Uncertainty 1		43	78	89	87
Fate Uncertainty 4		39	73	87	86
Base Case	Long-term	26	63	86	87
Fate Uncertainty 1		19	49	84	91
Fate Uncertainty 4		38	73	88	89

The base case and uncertainty simulation results all indicate that the model predicts the TCRA achieves significant relative reductions in water column TCDD concentration estimates. When looking at Year 1 of the simulation, the calculated percent reductions are relatively similar between the base case and the uncertainty bounds for all of the various averaging areas, with the uncertainty of the various percent reductions ranging from less than 1 percent to 5 percent. The following are the model's predicted results over the long term:

- When averaged over the USEPA's Preliminary Site Perimeter, the uncertainty range on the base case-predicted reduction in concentration of 26 percent is from 19 percent to 38 percent.
- Within the model grid cells corresponding to the lateral transect at River Mile 2.5, the long-term average percent reduction predicted by the model is 63 percent, with an uncertainty range of 49 percent to 73 percent.
- Within the footprint of the TCRA Site, long-term average estimated concentration reductions are similar between the base case and the uncertainty simulations (i.e., between 84 percent and 88 percent).
- Finally, at the smallest localized scale (i.e., a single model grid cell corresponding to the maximum predicted concentration in the vicinity of the TCRA Site), the base case model prediction and the uncertainty simulations all resulted in a nearly 90-percent reduction in peak TCDD concentration over the long term.

Overall, the results from these uncertainty analyses show that although there is uncertainty in the exact magnitude of model-predicted water column concentrations, there is relatively less uncertainty in the predicted relative reductions achieved by the TCRA, which average in the range of 30 percent within the USEPA's Preliminary Site Perimeter (uncertainty range of approximately 20 to 40 percent) to 90 percent in the localized areas of the TCRA Site (with uncertainty range of less than 5 percent). Water column concentrations in the immediate vicinity of the Armored Cap are not reduced completely due to various background sources, flux from sediments outside the limits of the TCRA Site, and transport associated with river currents and tidal circulation.

3.2.2.2 Surface Sediment

Model-predicted future rates of natural recovery in surface sediments, including the range of model uncertainty, were evaluated at various spatial scales over the Model Study Area using the long-term future simulation described above (i.e., starting from post-TCRA sediment concentrations and forecasting over the Future Projection Period). With regard to model uncertainty, in some cases, the four fate model sensitivity simulations described in Table 3-3 had differing effects on predicted long-term surface sediment concentrations in different portions of the Model Study Area; therefore, the figures described below contain results for all four sensitivity simulations compared with the base case predictions.

Figure 3-18 shows a time series of model-predicted surface (0- to 6-inch) sediment TCDD concentrations averaged over the USEPA's Preliminary Site Perimeter. This figure shows a base case predicted decrease in TCDD concentration of approximately 75 percent over the Future Projection Period (decreasing from an initial TCDD concentration of approximately 8 nanograms per kilogram [ng/kg] to 2 ng/kg by Year 21). To quantify the rate of decline, an exponential decay curve was fit through the model results, and the rate of decline was calculated (see example for the base case simulation shown as a dotted line on Figure 3-18); the model-predicted decline of TCDD in surface sediment concentrations within the USEPA's Preliminary Site Perimeter corresponds to a half-life of 11 years. Although the model results vary year-to-year due to differences in flow conditions (which drive differences in sediment transport), the nature of the predicted recovery curve (i.e., an exponential decline) exhibits an asymptotic behavior, which is expected because concentrations of dioxins/furans would be expected to approach regional background concentrations associated with remaining sources of dioxins/furans (i.e., point and non-point sources, transport from upstream) in the area. For the uncertainty simulations, this predicted decline ranges from more than 85 percent (Fate Uncertainty 1) to 40 percent (Fate Uncertainty 4), corresponding to half-lives that vary by about a factor of 2 from the base case, ranging from 7 years to 24 years (Figure 3-18). The faster rates of recovery predicted for the Fate Uncertainty 1 simulation are a result of a combination of increased sedimentation rates and decreased mixing within the bed for this simulation. Conversely, the slower rates of recovery predicted for the Fate Uncertainty 4 simulation are a result of lower sedimentation and increased mixing within the bed.

Figure 3-19 shows time-series plots of model-predicted surface (0- to 6-inch) sediment TCDD concentrations averaged over 1-mile reaches in the vicinity of the TCRA Site. Similar to the spatial averages calculated for the USEPA's Preliminary Site Perimeter, the 1-mile reach averages show a trend of decreasing surface sediment concentrations over the model simulation period. The predicted natural recovery in this area can be attributed to ongoing deposition of lower concentration sediments derived from upstream areas of the river. The 1-mile reach that includes the TCRA Site (River Miles 3 to 2) shows a predicted decrease in concentration consistent with that for the USEPA's Preliminary Site Perimeter (i.e., 75-percent decrease corresponding to an 11-year half-life, with an uncertainty range that varies by about a factor of 2 to 3 from the base case). These results also show year-to-year variability, which is a result of varying flow and sediment transport conditions. For example, the model predicts an increase in concentration during Year 5 within River Miles 3 to 2, which is a result of predicted erosion during the highest flow event included in the simulation (corresponding to a return period between 50 and 100 years, as discussed in Section 2.1), but that increase only has a temporary effect on the long-term average trend predicted within that 1-mile area. Predicted rates of natural recovery in the other 1-mile reaches are similar to that in the reach containing the TCRA Site (i.e., half-lives of approximately 10 years), with estimated uncertainty ranges of approximately a factor of 2 to 3 (i.e., half-life values ranging from approximately 5 to 35 years). In some cases, the year-to-year variability in surface sediment concentrations is greater than others; however, an important finding from these simulations is that, despite the relatively wide ranges in parameter values included in these various uncertainty simulations, the model predicts decreases in concentration in all cases and spatial scales over the long term.

Lastly, as described in Section 3.2.1, the Armored Cap was simulated by setting the sediment bed TCDD/TCDF concentrations to zero within the corresponding model grid cells (which eliminated flux of dioxins/furans from this area to the overlying water column). Figure 3-20 shows a time-series plot of the base case model-predicted surface sediment TCDD concentrations averaged over this area (i.e., the capped area). Because concentrations were initially set to zero in this area, Figure 3-20 can be used to evaluate the model's prediction of sediment re-equilibration levels within the surface of the Armored Cap. This figure shows predicted surface sediment TCDD concentrations increasing to approximately 2 ng/kg over the Future Projection Period. This predicted increase is a result of deposition of sediments from the surrounding areas of the river on the surface of the Armored Cap, and the concentration is generally consistent with regional background levels in surface sediment (e.g., Table 4-5 of the RI Report indicates TCDD background concentrations range from 0.01 to 5 ng/kg; Integral and Anchor QEA 2013).

4 MODELING TO SUPPORT EVALUATION OF REMEDIAL ALTERNATIVES

As described in Section 3.2.2.2 above, the post-TCRA future chemical fate model simulation was used to evaluate relative changes in surface sediment dioxin/furan concentrations over time (i.e., rates of natural recovery) in the Model Study Area. The results from this simulation apply to Alternatives 1N through 3N evaluated in the FS (as discussed in Section 4.1). Section 4.2 provides a description of additional model simulations that were conducted for FS Alternatives 4N, 5N, 5aN, and 6N, which include active remediation of sediments within the TCRA Site, as well as one other area within the USEPA's Preliminary Site Perimeter in the case of Alternative 6N. In addition to evaluating general long-term trends for these alternatives, the model's predictions of future sediment and water column dioxin/furan concentrations from these simulations were used to quantify potential short- and long-term impacts associated with the construction activities (i.e., sediment resuspension and release during remediation and effects of dredge residuals).[14]

4.1 Simulation of Natural Recovery for FS Alternatives

The predicted rates of natural recovery presented in Section 3.2.2.2 apply to Alternatives 1N through 3N for the FS. For the purposes of chemical fate and transport modeling, these alternatives can all be characterized by the post-TCRA future simulation because Alternatives 1N (No Further Action) and 2N (ICs and MNR) have no additional remedial activities, and Alternative 3N only includes construction of the Permanent Cap, which would not be expected to create any significant potential for construction-related releases of dioxins/furans. Therefore, there would be no significant differences in future surface water or sediment concentrations among Alternatives 1N through 3N; thus, the long-term chemical fate model predictions described in Section 3.2.2 would be the same for all three of these alternatives.

4.2 Simulation of Remediation Alternatives 4N, 5N, 5aN, and 6N

Additional simulations were conducted using the calibrated fate and transport model for FS Alternatives 4N, 5N, 5aN, and 6N, because these alternatives include active remediation of

[14] As noted previously, despite there being various sources of uncertainty associated with the model, they do not hinder the model's ability to evaluate remedial alternatives on a comparative (relative) basis, because most sources of uncertainty are common to all alternatives.

sediments that could affect long-term chemical fate and transport within the Model Study Area (due to resuspension and release during remediation and dredge residuals). The remediation components of these alternatives are as follows:

- Alternatives 4N and 5N include the same Permanent Cap as Alternative 3N, as well as partial remediation of sediments from portions of the TCRA Site. For Alternative 4N, this would consist of solidification/stabilization (S/S) of soils/sediments beneath the Armored Cap that have concentrations exceeding 13,000 ng/kg on a toxicity equivalent (TEQ) basis whereas for Alternative 5N, it would involve removal of those same materials, after which the remediated area would be backfilled and the Armored Cap would be replaced/reconstructed and then enhanced to create a Permanent Cap.
- Alternative 5aN includes partial removal of sediments exceeding the PCL for protection of the hypothetical recreational visitor (220 ng/kg TEQ) for the area within the Armored Cap with water depth shallower than 10 feet. Under this alternative, portions of the Armored Cap would remain in place and would be enhanced to create a Permanent Cap. A sand cover would be placed in the dredged areas following removal to address dredge residuals.
- Alternative 6N includes full removal of soils/sediments from the TCRA Site, as well as removal of sediments exceeding the PCL in one other area of the USEPA's Preliminary Site Perimeter. A sand cover would be placed following removal to address dredge residuals.

The simulations of these alternatives utilized the same 21-year future simulation length, hydrologic conditions, and boundary loads as described for the simulations of post-TCRA future conditions in Section 3.2.1. However, unlike the simulation of post-TCRA conditions, these simulations account for the effects of sediment remediation on dioxins/furans within the Model Study Area, and as such, required the following:

- "Mapping" of the remediation footprints onto the chemical fate model grid
- Specification of dioxin/furan releases during in-water construction activities associated with the sediment remediation
- Specification of post-remediation concentrations, including simulation of the effects of dredge residuals on sediment concentrations for certain cases

Details regarding the additional model setup required for simulation of these alternatives are provided in the subsection that follows.

4.2.1 Model Setup

4.2.1.1 Mapping of Remediation Areas onto the Model Grid

In order to simulate Alternatives 4N, 5N, 5aN, and 6N in the fate model, the footprint of the remediation area for each alternative was first “mapped” onto the fate model grid. As discussed in Section 4 of the FS, the remediation footprints are defined as follows:

- For Alternatives 4N and 5N, the footprint was based on the limited portion of the TCRA Site containing dioxin/furan concentrations in excess of 13,000 ng/kg on a TEQ basis. The resulting remediation footprint consists of two areas, which are termed the Eastern Cell and Western Cell (as defined in the FS; Figure 4-1). Because remediation of the Western Cell would be performed from land, releases during remediation would be expected to be minimal from that area; therefore, only the Eastern Cell was represented in the model simulations for these two alternatives.
- The Alternative 5aN dredging footprint was delineated to encompass the portion of the TCRA Site containing sediment samples with concentrations exceeding a PCL of 220 ng/kg TEQ and water depths shallower than 10 feet. Note that this area also includes all sample locations that exceed 13,000 ng/kg TEQ, as required by USEPA when they developed this alternative.
- The Alternative 6N dredging footprint was delineated to encompass all areas containing sediment samples with concentrations exceeding a PCL of 220 ng/kg TEQ. These areas included a large portion of the TCRA Site, as well as one sample polygon offshore of the San Jacinto River Fleet (SJRF) property (Figure 4-1).

These remediation areas were mapped onto the chemical fate model grid as shown on Figure 4-1.

4.2.1.2 Releases during Sediment Remediation

The model’s simulation of sediment remediation accounts for releases of dioxins/furans during construction by specifying a fraction of the chemical mass present in the remediated sediment (i.e., sediment that is removed in the case of Alternatives 5N, 5aN, and 6N, or that which undergoes S/S in the case of Alternative 4N) that could be released to the water column under the simulated conditions. Details on how this potential release was represented in the model are discussed below.

Potential releases of chemical mass during remediation activities were simulated in the fate model as a dissolved phase flux of dioxins/furans to the water column within each remediated grid cell. The magnitude of that release flux was determined based on the average concentration and depth of sediments removed (or subject to S/S in the case of Alternative 4N), an assumed fraction of dioxin/furan mass released, and the construction schedule associated with the removal or S/S activities (i.e., time it takes to remediate that grid cell based on the specified production rate for the alternative). For each remediation footprint, an average depth of remediation and volume-weighted average concentration within the remediation prism were calculated. These values were used in conjunction with each grid cell's surface area and bulk density to calculate the mass of dioxins/furans remediated for the purposes of the model's release calculation. The depths and concentrations used in these calculations are listed in Table 4-1.

Table 4-1
Average Remediation Depth and Volume-Weighted Average Sediment Concentration Used for Calculating Potential Releases During Construction

Alternative / Remediation Area	Average Depth of Remediated Sediment (feet)	Volume-Weighted Average Concentration in Remediation Prism	
		TCDD (ng/kg)	TCDF (ng/kg)
Alternatives 4N and 5N (Eastern Cell of footprint within TCRA Site)	7	5,600	23,800
Alternative 5aN (portion of TCRA Site with water depth < 10 feet)	6.75	5,100	15,800
Alternative 6N (TCRA Site)	6.75	4,300	13,100
Alternative 6N (polygon adjacent to SJRF property)	6	120	500

The dioxin/furan mass release fractions applied in the calculations are as follows:

- For simulation of S/S under Alternative 4N (Eastern Cell only) and sediment removal under Alternative 5aN (which would include the construction of an earthen berm and sheetpile wall as an engineered barrier to manage water quality during construction), a release rate of 0.85 percent was assumed. This value was based on the midpoint of the range of release values estimated from areas of the Hudson River in which sediment removal was performed within sheet pile walls (Anchor QEA and Arcadis 2010). This value is in the low end of the range observed from sites where dredge release has been measured. It was assumed for the purposes of these model simulations to be representative of releases that could occur when engineered barriers are utilized to manage water quality during construction (under Alternative 5aN) or due to disturbance of the sediments during S/S activities (under Alternative 4N).
- Simulation of release during sediment removal under Alternatives 5N (Eastern Cell only) and 6N assumed the fraction of dioxins/furans released during removal was 3 percent of the chemical mass removed. This value is based on case studies of dredging release at various contaminated sediment sites across the country, as summarized in Section 5.4.2 of the FS Report (see FS Table 5-2).

The mass of dioxin/furan released (calculated in each grid cell based on the average depth and concentration of remediated sediment and the assumed release rates as described above) was specified in the model to occur uniformly over the time needed to complete the in-water remediation activities of a given alternative. These times were estimated to be 1.5 months and 0.5 month for Alternatives 4N and 5N, respectively (Eastern Cell only), 8.5 months for Alternative 5aN, and 13 months for Alternative 6N; the start of remediation was specified to begin in the first year of the projection period for each alternative.

4.2.1.3 Sediment Bed Concentrations Following Remediation

Because the remediation activities for Alternatives 4N and 5N would include backfilling followed by replacement/reconstruction of the Armored Cap, it was assumed for the purposes of modeling that the surface sediment concentration within the remediated grid cells would be zero following construction, consistent with the method used to simulate the Armored Cap in the post-TCRA future simulation. However, due to the extensive removal under Alternatives 5aN and 6N, the remediation would be conducted through in-water construction techniques (dredging), followed by placement of a sand cover to manage residuals. Thus, an analysis of post-remediation sediment concentrations was needed for accurate simulation of that alternative in the model. The methods used for specifying post-remediation bed concentrations in the model to account for the Alternatives 5aN and 6N dredging are described below.

Sediment removal under Alternatives 5aN and 6N was simulated in the fate model by resetting the simulated sediment bed to reflect post-dredging conditions within the removal areas. The corresponding post-remediation sediment concentrations were specified to account for three factors: 1) sediment residuals that would be generated following dredging; 2) the observed concentration of the (un-dredged) sediment present beneath the neatline elevation of the last dredge pass; and 3) the placement of a sand cover following dredging to manage residuals.

The potential for generating residuals during dredging is well documented (e.g., Patmont and Palermo 2007; U.S. Army Corps of Engineers 2008a, 2008b; Bridges et al. 2010). Based on information regarding residuals generated at other sites where environmental dredging has been performed (e.g., Patmont and Palermo 2007; Bridges et al. 2010; Anchor Environmental 2007; Alcoa 2006), post-remediation sediment bed concentrations in areas subject to dredging were specified in the model as follows:

- Deep sediments (i.e., the bottom 39 inches of the simulated 48-inch sediment bed) were set to un-dredged sediment concentrations that were specified based on sampling data. Note that Alternative 6N includes two separate dredge areas (i.e., the TCRA Site and the polygon adjacent to the SJRF property); given the relatively small size of these two dredge areas (relative to the size of the overall model grid), the deep sediment concentration was defined as a single average concentration over each of these two areas.

- A 3-inch layer of dredge residuals was assumed to be generated above the deeper un-dredged sediments;[15] dioxin/furan concentrations in the residual layer were assumed to be equal to sediment concentrations in the deepest samples above the specified dredge depths, which were considered representative of the last dredge pass (Patmont and Palermo 2007; Bridges et al. 2010). In other words, because Alternatives 5aN and 6N include removal of sediments exceeding the PCL (220 ng/kg TEQ), the residual layer concentration was defined based on sampling data collected immediately above the 220 ng/kg TEQ depth horizon (which in many cases was greater than 220 ng/kg TEQ). As with the deep concentrations, the residual layer concentrations were defined as a single average concentration over the footprint of each dredge area.
- The top 6 inches of the simulated bed sediment in each dredge area was assumed to consist of a residual cover (e.g., sand); dioxin/furan concentrations in this cover material were assumed to be 5 percent of the dredge residual concentrations (due to mixing when the cover is placed). This value was specified based on experience from other dredging projects (e.g., Alcoa 2006; Anchor Environmental 2007).

Table 4-2 provides a summary of the concentrations of TCDD and TCDF specified for the various model bed layers described above under Alternatives 5aN and 6N. These concentrations were calculated based on the same surface and subsurface sediment core data used to determine the horizontal and vertical extents of removal as described in Section 4 of the FS.

[15] The 3-inch residual layer thickness was specified based on an assumed average 6-foot dredge cut plus 1-foot over-dredge, with 5-percent sediment loss (i.e., [6 feet + 1 foot] * 0.05 = 4.2 inches); this thickness was rounded down to 3 inches, which is the thickness of a single model sediment bed layer.

Table 4-2
Summary of Post-Remediation Sediment Bed Concentrations for Alternatives 5aN and 6N

Alternative / Remediation Area	Model Bed Layer	TCDD (ng/kg)	TCDF (ng/kg)
Alternative 5aN (portion of TCRA Site with water depth < 10 feet)	Top 6 inches (residual cover)	*(3,956 × 0.05)* = 198	*(9,979 × 0.05)* = 499
	Next 3 inches (residual layer)	3,956	9,979
	Bottom-most 39 inches (un-dredged sediment)	37	107
Alternative 6N (TCRA Site)	Top 6 inches (residual cover)	*(3,956 * 0.05)* = 198	*(9,979 * 0.05)* = 499
	Next 3 inches (residual layer)	3,956	9,979
	Bottom-most 39 inches (un-dredged sediment)	37	107
Alternative 6N (polygon adjacent to SJRF property)	Top 6 inches (residual cover)	*(224 * 0.05)* = 11	*(1,050 * 0.05)* = 53
	Next 3 inches (residual layer)	224	1,050
	Bottom-most 39 inches (un-dredged sediment)	6	17

4.2.2 Results

This subsection presents the results from the fate and transport model long-term (21-year) simulations of Alternatives 4N, 5N, 5aN, and 6N for TCDD (results for TCDF are contained in Attachment 1). For comparison purposes, the water column and sediment TCDD concentration estimates predicted for these three alternatives are presented together on overlay plots, along with those from the simulation of post-TCRA future conditions (representative of Alternatives 1N through 3N) described in Section 3.2.2. Hereafter in this appendix, the post-TCRA future simulation is referred to as "Alternatives 1N through 3N."

4.2.2.1 Water Column

Longitudinal profiles of predicted water column TCDD concentration estimates during the first year of the simulation are shown on Figure 4-2a. As shown on this figure, predicted lateral average water column concentration estimates for Alternatives 4N, 5N, 5aN, and 6N all exhibit substantial increases in the vicinity of the TCRA Site relative to the simulation for Alternatives 1N through 3N. These predicted increases are a result of simulated releases of TCDD during remediation within the TCRA Site for these alternatives (which is simulated to occur over the first month or two for Alternatives 4N and 5N, the first 8.5 months for

Alternative 5aN, and the first 13 months of the simulation for Alternative 6N). The magnitude of these predicted increases is proportional to the volume of remediated sediment and the assumed release rate associated with the construction techniques (discussed in Section 4.2.1.2 above). Relative to Alternatives 1N through 3N, the Year 1 average concentrations in the area of the TCRA Site are predicted to increase by approximately 10-, 50-, 90- and more than 100-fold for Alternatives 4N, 5N, 5aN, and 6N, respectively, as a result of the simulated TCDD releases during remediation. Several years following the simulated remediation, as represented by model results from simulation Year 11 (Figure 4-2b), differences in predicted water column concentration estimates between the Alternatives 1N through 3N simulation and results for Alternatives 4N, 5N, 5aN, and 6N are much smaller. Concentration estimates throughout the USEPA's Preliminary Site Perimeter predicted for Alternatives 4N and 5N in Year 11 are indistinguishable from those predicted for Alternatives 1N through 3N, and those for Alternatives 5aN and 6N are only slightly higher than Alternatives 1N through 3N (i.e., increases of 50 percent or less for Alternative 5aN and 70 percent or less for Alternative 6N), due to elevated flux from sediments (discussed more below).

Figure 4-3 shows time-series plots of model-predicted monthly average water column TCDD concentration estimates averaged over the USEPA's Preliminary Site Perimeter and within the footprint of the TCRA Site for the various alternatives (i.e., Alternatives 4N, 5N, 5aN, 6N, and Alternatives 1N through 3N). This figure also shows the large predicted increases in water column concentration estimates during Year 1 of the simulations for Alternatives 4N, 5N, 5aN, and 6N (relative to Alternatives 1N through 3N), within both averaging areas; the timing of these increases corresponds directly to the simulated remediation durations associated with these alternatives. After the simulated remediation is complete, the results for Alternatives 4N/5N and 5aN/6N exhibit differing behavior, as follows:

- Average water column concentration estimates within the USEPA's Preliminary Site Perimeter for Alternatives 4N and 5N are predicted to decrease to levels consistent with those predicted under Alternatives 1N through 3N following the simulated remediation (Figure 4-3, middle panel). Similar results are predicted for average water column concentrations within the footprint of the TCRA Site (Figure 4-3, bottom panel), although the Alternative 4N/5N results are predicted to be slightly elevated as compared to Alternatives 1N through 3N.

- For Alternatives 5aN and 6N, the average water column concentration estimates predicted within the USEPA's Preliminary Site Perimeter generally track those predicted for the Alternatives 1N through 3N simulation following remediation (i.e., after Year 1); however, the Alternatives 5aN and 6N results are generally higher than those of Alternatives 1N through 3N. Results for Alternative 6N are approximately double those of Alternatives 1N through 3N for approximately 5 years after completion of the simulated dredging (and results for Alternative 5aN are somewhat lower than those of Alternative 6N but still higher than those for Alternatives 1N through 3N). The predicted increases under these two alternatives are indicative of potential for long-term impacts in some areas. Longer term, water column concentration estimates within the USEPA's Preliminary Site Perimeter predicted for Alternative 5aN and 6N approach those of Alternatives 1N through 3N (i.e., approximately 11 years after remediation), as lower concentration sediments are deposited in that area. Average concentrations within the TCRA Site for Alternative 5aN and 6N are also predicted to decrease after the simulated dredging. Ten years after remediation, the results for Alternatives 5aN and 6N are approximately two to four times higher than those predicted under Alternatives 1N through 3N (with results for Alternative 6N being somewhat higher than those predicted for Alternative 5aN). By the end of the Future Projection Period, the difference between Alternatives 1N through 3N and Alternatives 5aN and 6N decreases to about a factor of two. This predicted difference between Alternatives 5aN/6N relative to Alternatives 1N through 3N is due to a combination of sediment residuals generated during dredging within the TCRA Site (i.e., higher concentration sediments at depth are brought to the surface as residuals during removal and subsequently simulated to be entrained within the residual cover) and TCDD that is redistributed following release during dredging; these two factors are discussed further below.

4.2.2.2 Surface Sediment

Time series of model-predicted surface sediment TCDD concentrations averaged over the USEPA's Preliminary Site Perimeter for Alternatives 1N through 3N and Alternatives 4N, 5N, 5aN, and 6N are shown on Figure 4-4. This figure shows that the average surface sediment concentrations within this area are predicted to increase in Year 1 under

Alternatives 4N, 5N, 5aN, and 6N, as compared to Alternatives 1N through 3N. The magnitudes of these increases differ for each alternative, with those for Alternatives 4N and 5N being 1 and 2 ng/kg (approximate increases of 12 percent and 25 percent), respectively, whereas the concentrations predicted for Alternatives 5aN and 6N at the end of Year 1 represent an approximate two- and three-fold increase, respectively, relative to Alternatives 1N through 3N. The large predicted increases for Alternatives 5aN and 6N are due in part to high concentration sediment residuals that are generated during the simulated dredging within the TCRA Site. The predicted increases for Alternatives 4N and 5N, as well as a majority of those predicted for Alternatives 5aN and 6N, are due to fluxes of dissolved dioxins/furans simulated to be released during remediation that partition onto suspended sediments and are subsequently re-deposited both within and outside of the TCRA Site. Following these initial increases, the surface sediment concentrations predicted for Alternatives 4N, 5N, 5aN, and 6N generally track those of the Alternatives 1N through 3N simulations, declining at an average half-life of about 10 years (albeit at higher concentrations, especially for Alternatives 5aN and 6N).

Figure 4-5 shows time-series plots of surface sediment TCDD concentrations averaged over 1-mile reaches within the vicinity of the TCRA Site. The river mile that includes the TCRA Site (River Miles 3 to 2) shows initial increases in sediment concentration for Alternatives 4N, 5N, 5aN, and 6N that are similar to those shown on Figure 4-4 (i.e., approximately 20 to 30 percent for Alternatives 4N and 5N, two-fold for Alternative 5aN, and almost three-fold for Alternative 6N). For the remaining three 1-mile reaches, the predicted sediment concentrations under Alternatives 4N and 5N are similar to or slightly higher in some cases (e.g., Alternative 5N in River Miles 4 to 3) than those predicted under Alternatives 1N through 3N. The predicted sediment concentrations for Alternative 5aN are somewhat higher than those for Alternatives 1N through 3N, 4N, and 5N; however, the results for Alternative 6N show noticeable predicted increases in concentration relative to Alternatives 1N through 3N, 4N, 5N, and 5aN in all three one-mile reaches (although the absolute magnitude of these increases is small in some cases; e.g., 1 to 2 ng/kg in River Miles 5 to 4). The larger increase observed under Alternative 6N are due to dissolved TCDD that was simulated to be released during remediation within the TCRA Site, and was predicted to partition onto suspended sediments that were being transported in the area and subsequently deposited outside of the TCRA Site. The larger increase predicted for River Miles 3 to 2 under Alternatives 5aN and 6N is also due in part to the simulated sediment residuals generated during dredging within the TCRA Site. The effects of dredge release and subsequent redistribution for Alternative 5aN and 6N are further explored through the graphics described below.

The effects of redistribution of TCDD following release during remediation, as predicted by the model, are further evident when surface sediment concentrations are viewed on a model grid cell basis. Figures 4-6a, 4-6b, 4-6c, and 4-6d present maps of model-predicted surface sediment concentrations at the end of simulation Year 1 for Alternatives 4N, 5N, 5aN, and 6N, respectively. Each figure shows the results from the Alternatives 1N through 3N simulation on the left panel (for comparison), the results for the given alternative on the center panel, and the difference between concentrations predicted for the given alternative and Alternatives 1N through 3N on the right panel (positive values on these panels indicate a predicted increase in concentration relative to Alternatives 1N through 3N). These figures illustrate the predicted spatial patterns of TCDD redistribution following release during remediation for Alternatives 4N, 5N, 5aN, and 6N, as indicated by the areas of increased concentrations surrounding the TCRA Site. The magnitude of these increases and spatial extent over which they occur differs by alternative, according to the magnitude of TCDD mass simulated to be released during remediation. For example, for Alternative 4N, a relatively small zone of increases in the range of 1 to 3 ng/kg is predicted (Figure 4-6a), with larger increases of 3 to 10 ng/kg predicted within the TCRA Site. The corresponding areas of similar increases are larger for Alternative 5N (Figure 4-6b), with increases of 3 to 10 ng/kg extending beyond the TCRA Site and downstream of the I-10 Bridge, and increases of 1 to 3 ng/kg occurring over half of the USEPA's Preliminary Site Perimeter. Alternative 5aN shows a larger area of redistribution, with increases of 1 to 3 ng/kg predicted throughout most of the USEPA's Preliminary Site Perimeter, increases of 3 to 10 ng/kg throughout a large fraction of that area, and increases of 10 to 30 ng/kg in a small area near the TCRA Site. The redistribution following the simulated Alternative 6N dredge release is even more extensive; it is predicted to result in increases in 3 to 10 ng/kg over most of the USEPA's Preliminary Site Perimeter, with increases of over 30 ng/kg immediately adjacent to the TCRA Site.

Model results averaged over the TCRA Site are shown on Figure 4-7. As described in Section 3.2.2.2, the results for Alternatives 1N through 3N shown on this plot represent the average

TCDD concentration in sediments that deposit on the surface of the Armored Cap (which approach 2 ng/kg at the end of the Future Projection Period). The results for Alternatives 4N, 5N, 5aN, and 6N show differences relative to Alternatives 1N through 3N that reflect the effects of simulated release/redistribution and dredge residuals in the case of Alternatives 5aN and 6N. For Alternatives 4N and 5N, the effects of simulated release during remediation within the TCRA Site and subsequent redeposition causes predicted TCDD concentrations to increase to 30 and 40 ng/kg, respectively. The model's representation of dredging conducted under Alternatives 5aN and 6N results in an average surface sediment concentration in this area that is more than two orders of magnitude higher than Alternatives 1N through 3N (i.e., over 200 ng/kg). This value is consistent with the concentrations of the residual covers specified in this area (see Table 4-1) but higher as a result of TCDD that was predicted to be released during dredging and subsequently redeposited in that area. Following these initial increases associated with remediation, the concentrations within the TCRA Site are predicted to decrease by approximately a factor of two over the remainder of the simulations of Alternatives 4N, 5N, 5aN, and 6N, as a result of deposition of sediments derived from upstream areas.

Overall, the simulations of Alternatives 4N, 5N, 5aN, and 6N indicate that short- and long-term impacts associated with simulated releases during sediment remediation and dredge residuals in the case of Alternative 5aN and 6N are predicted to result in increases in estimated surface water and surface sediment concentrations when compared to the Alternatives 1N through 3N simulation. The magnitudes of these increases differ by alternative and the spatial scale over which model results are averaged, with those associated with Alternative 6N and the small scale of the TCRA Site area being the largest.

5 SUMMARY

The modeling framework developed in the Chemical Fate and Transport Modeling Study was used as a tool for evaluating remedial alternatives in the FS.

As directed by USEPA (Miller 2012, pers. comm.), additional hydrodynamic and sediment transport model sensitivity analyses were first conducted. Analyses using an alternate data source to specify WSE at the downstream hydrodynamic model boundary indicated minimal effect on sediment transport within the USEPA's Preliminary Site Perimeter. Model simulations were conducted to evaluate high-flow events with return periods of 2, 10, and 100 years. Within the USEPA's Preliminary Site Perimeter, the model predicted areas of both net deposition and net erosion for these flood event simulations, with increases in the area and depth of erosion with increasing return period flows. In general, depths of erosion and deposition within the corresponding areas during these events were predicted to average a few cm or less, with bed scour greater than 10 cm only being predicted in a limited area for the 100-year event. Longer-term simulations that include the effects of an approximate 100-year flood event indicate that following such erosion during flood events, the system recovers, consistent with its state of long-term net deposition.

The chemical fate model was then used to develop future predictions of dioxin and furan concentrations in sediment and surface water within the Model Study Area. Simulations were first conducted for post-TCRA future conditions by configuring the model to represent the Armored Cap at the TCRA Site. This included changing sediment transport model inputs to reflect the characteristics of the Armored Cap and setting the chemical concentration of the corresponding grid cells to zero in the chemical fate and transport model (to represent the Armored Cap's elimination of dioxin/furan flux to the surface water). The model was run for a 21-year future period based on the hydrologic record from 1990 through 2011 that included wide variations in flows and tidal conditions, including an approximate 100-year event. These post-TCRA future simulations were also conducted with alternate sets of model input parameters, for both sediment transport and chemical fate, to develop uncertainty bounds on the model predictions.

By comparing results from the post-TCRA simulations to those from similar simulations conducted based on pre-TCRA sediment concentrations, the model was used to evaluate the effects of the TCRA on surface water dioxin and furan concentration estimates within the Model Study Area. The chemical fate model predicted significant improvements in surface water concentrations as a result of the TCRA; reductions were predicted over several spatial scales. Within the USEPA's Preliminary Site Perimeter, surface water concentration estimates were predicted to be reduced by a factor of 2 to 3 (with the post-TCRA concentrations being driven by sources of dioxins/furans from upstream transport and point and non-point sources in the Model Study Area). These findings were not significantly affected by the model uncertainty analysis, which provided quantitative bounds on these reductions. However, it should be noted that the underlying water column dataset used to develop and calibrate the fate and transport model was smaller than the sediment data, imparting some uncertainty in the predictions of absolute concentrations.

The long-term post-TCRA simulations were also used to predict rates of natural recovery in surface sediments; these predictions are representative of FS Alternatives 1N, 2N, and 3N. The model predicted long-term declines in average surface sediment concentrations throughout the USEPA's Preliminary Site Perimeter consistent with an approximate 10-year half-life. Although there are periods of variability in the predicted surface sediment concentration trends that coincide with variations in flow and sediment transport conditions (e.g., periodic erosion), the longer-term predicted trends are characterized by declines throughout the simulation. Uncertainty analyses conducted for these simulations did not produce significantly differing results—despite the relatively wide ranges in parameter values evaluated, the model predicted long-term declines in surface sediment concentration in all cases and spatial scales. The model also predicted average surface sediment concentrations in the Armored Cap, which initially were set to zero, to increase to a level that approaches regional background concentrations.

Finally, simulations were conducted for the active sediment remediation alternatives (i.e., partial S/S and removal within the TCRA Site for FS Alternatives 4N and 5N, respectively, extensive sediment removal within the TCRA Site for Alternative 5aN, and extensive sediment removal within the TCRA Site and one other area for Alternative 6N). In addition to evaluating general long-term trends for these alternatives, the model was used to quantify potential short- and long-term impacts associated with the sediment remediation activities (i.e., sediment resuspension and release during remediation and the effects of dredge residuals). Within and outside the TCRA Site, the model predicted large increases in surface water concentrations during Year 1 of the simulations of Alternatives 4N, 5N, 5aN, and 6N (relative to the simulation of Alternatives 1N through 3N). These short-term increases in predicted surface water concentrations ranged from approximately an order of magnitude for Alternative 4N to greater than two orders of magnitude for Alternative 6N, and were due to simulated releases during remediation. Following the initial simulated remediation period, model results for Alternatives 4N and 5N showed little to no increase in surface water concentration estimates relative to Alternatives 1N through 3N, whereas predicted concentrations for Alternatives 5aN and 6N remained higher than the Alternatives 1N through 3N simulation by a factor of 2 or more within the footprint of the TCRA Site throughout the duration of the long-term simulation. Increases in surface sediment concentration in and around the TCRA Site (relative to Alternatives 1N through 3N) were also predicted for Alternatives 4N, 5N, 5aN, and 6N. These increases were a result of simulated dissolved phase releases during remediation that partition onto suspended sediments as they are transported in the area and subsequently deposit on the sediment bed, as well as dredge residuals in the case of Alternative 5aN and 6N. The magnitude of these increases differed by alternative and also by the spatial scale over which the model results were averaged, with those associated with Alternatives 5aN and 6N and the small scale of the TCRA Site area being the largest. The spatial extent of these predicted increases was also greatest for Alternatives 5aN and 6N, for which increases were predicted to occur over large portions of the USEPA's Preliminary Site Perimeter.

Overall, the results from the post-TCRA simulations of natural recovery (i.e., Alternatives 1N, 2N, and 3N) and the simulations of the active sediment remediation alternatives (i.e., Alternatives 4N, 5N, 5aN, and 6N) provide predictions of long-term relative changes in surface water and sediment dioxin/furan concentrations, as well as quantitative estimates of the potential short- and long-term effects of sediment remediation, that were used to support the comparative evaluation of alternatives conducted in the FS.

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ATTACHMENT 1 (ON CD)
COMPLETE SET OF MODEL OUTPUT GRAPHICS FOR TCDD AND TCDF